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The January 10, 1997 auroral hot spot, horseshoe aurora and first substorm: A CME loop?

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Abstract. The January 10, 1997 interplanetary high-speed stream and the resultant first substorm (~0332 to 0334 UT onset) is studied. A 47 minute interval of relatively intense southward interplanetary magnetic field (IMF) (B_S = 4 to 8 nT) bounded by two tangential discontinuities (TDs) is identified between the interplanetary shock and the magnetic cloud. The two discontinuities arrive at the magnetopause at ~0219 and ~0302 UT. The IMF B_S event served primarily to transfer solar wind energy to the magnetosphere/magnetotail, as no substorm expansion phase occurred during the event. The eventual energy release was in the form of a large substorm expansion phase which occurred after (~15-17 min.) a second IMF northward turning (after the end of the B_S interval). The interplanetary B_S event came after a prolonged northward IMF interval. During the initial part of the B_S event, both polar cap Sun-Earth aligned arcs formed (part of a theta aurora) and an auroral hot spot along the main arc took place. Later, during the B_S interval, an aurora in the shape of a horseshoe developed at lower (60°) latitudes (an oval with a gap in the noon sector). The dawnside portion of the horseshoe aurora became much brighter than the duskside with increasing time. The dawnside polar cap boundary layer (PCBL) broadband waves were well correlated with low energy ion fluxes (H^+, He^{++}, O^+) during the event. It is speculated that this IMF B_S structure may be an outer loop of the CME coming from the Sun. Another similar loop is identified just adjacent to the cloud.

Introduction

The purpose of this paper is to study an interplanetary B_S feature ahead of a magnetic cloud and its related auroral and magnetospheric responses. During this IMF B_S event, theta auroras, a midnight hot spot and an eventual asymmetric horseshoe aurora formed. A substorm expansion phase took place after the IMF B_S event had passed. The time sequences of the above, and the various interplanetary, magnetospheric and ionospheric phenomena will be discussed.

Data Analysis

This study utilizes the Wind plasma and magnetic field data, Polar ultraviolet images, plasma wave data, and low energy ion data, and the CANOPUS ground magnetograms. Detailed instrument descriptions can be found in *The Global Geospace Mission*. The Wind spacecraft was located at a geocentric solar ecliptic (GSE) position (x, y, z) of 86 R_E, -59 R_E, -4 R_E, where R_E is the Earth's radius. This location, calculated discontinuity orientations, and the measured solar wind velocities are used to determine the time delays between detection of interplanetary structures at Wind and convection of these structures to the Earth's magnetopause.

The Polar orbit has an 86° inclination with a ~9 R_E apogee and a ~1.8 R_E perigee. Since the beginning of the mission, the Polar apogee has been over the northern polar region.

Results

Interplanetary

The Wind interplanetary data for the first 6 hours of January 10 are shown in Figure 1. The IMF is plotted in geocentric solar-magnetospheric (GSM) coordinates. A large interplanetary ram pressure wave occurs at ~0053 UT. The onset of the wave is identified by the abrupt increases in plasma density and thermal speed, solar wind velocity and magnetic field strength. The compression of the magnetosphere by the increased ram pressure from the stream led to a faint UV auroral intensification (not shown) which propagated along the auroral oval from noon towards the tail and also in the magnetosphere from high L to low L. There was no substorm expansion phase caused by this compression, but there were a series of pseudobreakups (to be addressed in a separate paper).

Beginning with the compression wave, the IMF has a long duration northward component. At 0205 UT the IMF turns southward and remains southward until 0252 UT, when the field abruptly turns northward again. The B_S magnitude is initially ~4 nT. It more or less monotonically increases to ~8 nT before the abrupt northward turn. This interval of interest is shaded and the southward IMF interval is crosshatched. It should be noted that there is a slight velocity jump (from 430 to 440 km s^{-1}) at the leading edge of the B_S interval. This event precedes the magnetic cloud event [*Burlaga et al.*, 1998], whose onset is much later at ~0459 UT. A second and more permanent IMF northward turning occurs at 0307 UT.

Minimum variance analyses have been performed on the discontinuities bounding the B_S event (at the edges of two shaded regions). The maximum, intermediate and minimum eigenvectors are identified by the subscripts 1, 2 and 3, respectively. The discontinuity at 0205 UT has a normal direction of (0.88, 0.22, 0.42) in GSE coordinates. The value of the field along the normal direction, normalized by field magnitude, is 0.1. The second discontinuity at 0252 UT has a normal direction of (0.75, 0.43, 0.50) and has a normalized field along the minimum variance direction of 0.01. The low field component along the normal directions implies that both discontinuities are most likely tangential (TD) in nature. Although Alfvén waves and rotational discontinuities have been shown to be smaller in scale than the Earth's magnetosphere [*Tsurutani et al.,* 1990], tangential discontinuities are believed to be much larger in scale. One interpretation of this B_S event is that it is associated with a plasma slab bounded by TDs.

The arrival times of the discontinuities at the Earth's magnetopause are calculated using the spacecraft location, the solar wind convection speeds (430 km s^{-1} and 450 km s^{-1}, respectively) and the discontinuity orientations. The predicted arrival times at the Earth's magnetopause are 0220 UT and 0302 UT. We have also used the Geotail magnetic field measurements as a check for the delay time. The Geotail data (not shown) clearly show the same IMF B_S event. The Geotail/Wind magnetic field intercomparison for this event and several other related figures can be found in a companion paper [*Tsurutani et al.,* 1998a]. The times of arrival of these discontinuities at Geotail were ~0219 UT and ~0302 UT, respectively. At these times, Geotail was in the Earth's magnetosheath at (9.0 R_E, -4.5 R_E, 1.1 R_E) and (9.3 R_E, -3.4 R_E, 1.1 R_E), roughly 0.5 R_E upstream of the nominal magnetopause. This good agreement between the calculations and Geotail strongly support the idea that this B_S interval can be viewed as a large-scale convected structure.

The interplanetary magnetic cloud at 0459 UT is identified by the low proton density (1-2 cm^{-3}), the low temperature (thermal speed V_{th} ~20 km s^{-1}), and the intense magnetic fields (>12 nT). There is, however, a region just prior to the cloud proper which is also of interest. It occurs from 0441 to 0459 UT and it is shaded for emphasis (second shaded region) in Figure 1. The proton density and temperature (thermal speed) are considerably higher than the corresponding values within the magnetic cloud, and they are also lower than the values that occur just prior to the event. The magnetic field magnitude is intermediate between the cloud-proper values and the values slightly earlier in time. A case when plasma and fields had values intermediate between sheath and magnetic cloud plasma and fields, and was located upstream of the cloud, has been reported by *Galvin et al.* [1987].

UV Aurora

The UV aurora corresponding to the time interval of the southward IMF is shown in Figure 2. We show the UV images corresponding to the IMF event and slightly beyond: 0223 UT to 0340 UT. The Lyman-Birge-Hopfield (LBH) long band (~1700 Å) images proceed from top left, across and then down. In each image, noon is near the top.

What is quite remarkable is that the aurora is generally faint throughout the southward B_S interval, with no substorm expansion phase onsets. At the beginning of the IMF B_S interval, there are polar arcs and a very faint auroral oval at high latitudes. There is a "hot spot" at local midnight. The hot spot has a size range of 2° to 5° and brightens and dims over time (not shown). The relative location is stable. It is originally located where a polar arc "touches" the oval, and it becomes well poleward of the oval as the oval recedes equatorward. The hot spot lasts from prior to 0219 to 0239 UT. During this time period, the IMF B_y (the dawn-dusk component) was positive and decreased with time. These general features of the theta aurora are in good agreement with the model of the theta aurora proposed by *Newell and Meng* [1995] and *Chang et al.* [1998].

During the polar arc and the "hot spot" periods, a regularly shaped aurora formed, but at lower latitudes. From 0251 UT onward, a clear "horseshoe-shaped" aurora was present. The UV aurora is in the shape of an oval, but with part of the oval missing (a midday "gap" [*Dandekar and Pike,* 1978] from ~10 to ~14 LT), thus giving the shape of a horseshoe. The auroral intensity is continuous throughout the midnight sector with no particularly remarkable features.

Throughout the 47 minute IMF B_S interval, there was no significant expansive phase activity. This may well be due to the presence of northward IMF fields during the previous hour. The magnetosphere could have been brought to a low level "ground state" by the northward field.

From 0312 UT until 0334 UT, the horseshoe aurora becomes asymmetric in brightness, with the dawnside aurora becoming far brighter than the duskside. This brightening on the dawnside increases with time. High latitude magnetometer data (not shown here) indicate that a weak westward electrojet (~-300 nT) was peaked at ~0530 MLT, coinciding with the peak in the dawn-side luminosity.

At 0334 UT (with an uncertainty of ~-2 min.), the first hint of a substorm expansion phase onset is noted by a small hot spot at local midnight within the auroral oval. The Greenland magnetometer identified the onset at essentially the same time, and its maximum intensity was only ~-200 nT. The "hot spot" is indeed a spot on this scale. In subsequent images, the auroral substorm becomes fully developed (see 0340 UT).

Substorm Trigger? IMF B_N Turning?

The sharp northward IMF turning occurred at 0302 UT at Geotail. A second and more permanent B_N turning occurred 15 min. later (see Figure 1). The substorm onset time was 0332 to 0334 UT. Thus the delay for the first B_N turning would be ~30-32 min., and 15-17 min. for the second B_N turning. Since the substorm onset was 0332-0334 UT, the delay for the second B_N turning is 14 to 17 min. *Lyons et al.* [1997] have determined that the delay between IMF B_N triggers at the magnetopause and substorm onsets is ~9 ± 4.5 min.

Plasma Waves

There has been speculation that low latitude boundary layer (LLBL) waves can cause the quiet time dayside aurora. The question here is do they cause the horseshoe aurora and can they explain the dayside brightening? The Polar plasma wave sweep frequency receiver (SFR) data was analyzed (but not shown). The spacecraft was in a dawn-dusk trajectory. At the time of the IMF B_S event, the spacecraft was at local dawn (~6.3 MLT) at a distance of ~7.5 R_E. At this time, the broadband plasma waves having frequencies from 26 Hz to a few times 10^3 Hz were relatively weak compared to other intervals previously examined [*Tsurutani et al.*, 1998b]. The waves were well correlated with energetic ions. There is no remarkable wave feature between 0310 to 0334 UT when the horseshoe aurora develops and the dawn-dusk auroral brightness asymmetry becomes apparent. There is also no remarkable wave feature (or dawnside auroral features) during substorm onset at 0334 UT.

One of us (Y. Kamide) has examined the intensity and distribution of the field-aligned currents using over 57 northern auroral zone magnetometer stations (not shown). We find that the dawnside currents are significantly more intense than duskside currents at this time, similar to the UV imaging results.

Conclusions

We have demonstrated that a IMF B_S event, which had a long duration (47 min.) intense southward B_z field ($B_S = 4$ to 8 nT), only led to the development of a horseshoe-shaped aurora with no substorm expansion phases. The end of the 47 min. interval of IMF B_S was abruptly terminated by a short-lived northward turning. The substorm expansive phase onset occurred 15-17 min. after a second and much more permanent B_N turning that occurred 15 min. after the first.

During the middle portion of the IMF B_S interval, formation of a stable, low altitude (60°) horseshoe shaped aurora occurred. During this interval, precipitation in the polar regions all but disappeared. It should be noted that the horseshoe aurora is considerably different in shape and interplanetary IMF dependence than "horsecollar" auroras [*Cumnock et al.*, 1997].

IMF B_S Event: A Loop?

There is a great deal of similarity between the magnetic field and plasma characteristics in the second shaded region of Figure 1 to that of the event of study (first shaded region). In both regions, $B_x > 0$, $B_y > 0$ and $B_z < 0$. The field magnitudes are both ~8-10 nT and the proton thermal velocities ~30 km s^{-1}. The discontinuities at the boundaries of the second region (0441 UT and 0459 UT) have also been studied using minimum variance analyses (not shown). It is found that the normals of these discontinuities are closely aligned with those of the former event. Thus one very interesting possibility is that these two structures are outer loops of the CME (a schematic is shown in Figure 3). If such loops can be identified, and their field orientations are the same as the subsequent magnetic cloud, they could be extremely useful in the prediction of impending magnetic storms.

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Figure 1. The Wind solar wind plasma and magnetic field data.

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Figure 2. The Polar UV aurora from 0223:50 UT to 0340:30 UT. Local midnight is at the bottom of each panel. Time increases from the upper left to the upper right.

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Figure 3. A schematic of the large scale outer loop which leads to the auroral hotspot, the theta aurora, and the horseshoe aurora. It is believed that two such loops have been identified in the Wind magnetic field data.

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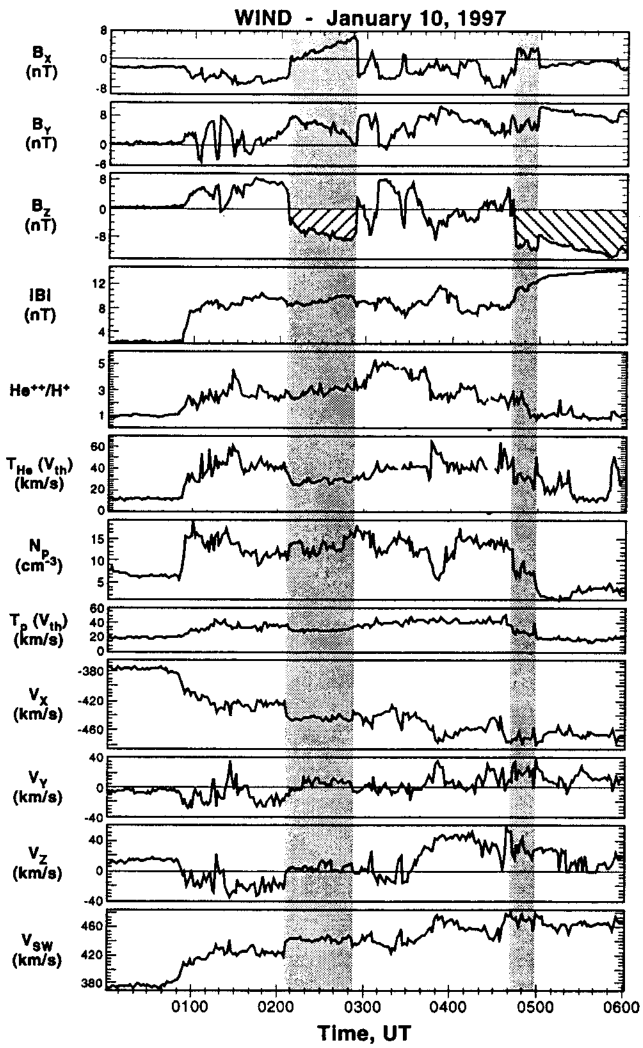
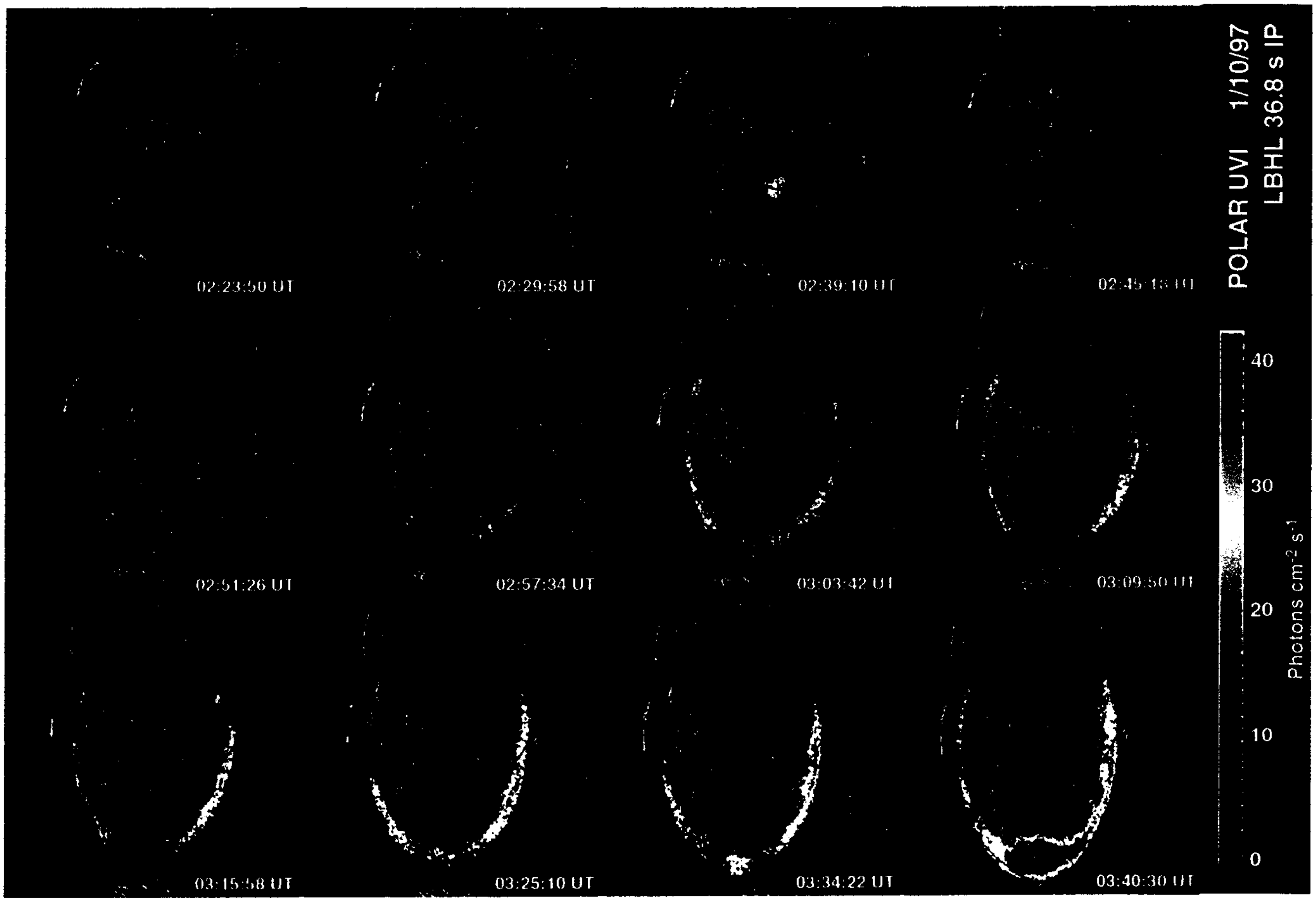


WIND - January 10, 1997
Bx (nT)
By (nT)
Bz (nT)
|B| (nT)
He++/H+
THe (Vth) (km/s)
Np (cm-3)
Tp (Vth) (km/s)
Vx (km/s)
Vy (km/s)
Vz (km/s)
VSW (km/s)
0100 0200 0300 0400 0500 0600
Time, UT

Figure 1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LBHL 36.8 s IP
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02:39:10 UT
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02:57:34 UT
03:03:42 UT
03:15:58 UT
03:25:10 UT
03:34:22 UT
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40
30
20
10
0
Photons cm-2 s-1

Figure 2

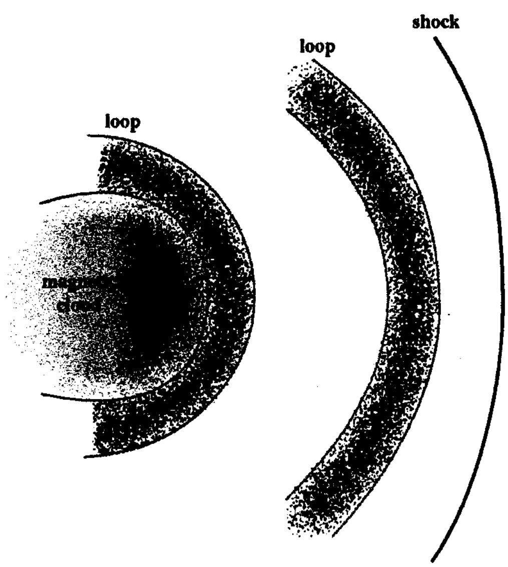

Figure 3